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MISSING BARYONS, FROM CLUSTERS TO GROUPS OF GALAXIES

A. CAVALIERE[1] AND A. LAPI[1,2]

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ABSTRACT

From clusters to groups of galaxies, the powerful bremsstrahlung radiation L_X emitted in X rays by the intracluster plasma is observed to decline sharply with lowering virial temperatures T (i.e., at shallower depths of the gravitational wells) after a steep local $L_X - T$ correlation; this implies increasing scarcity of diffuse baryons relative to dark matter, well under the cosmic fraction. We show how the widely debated issue concerning these 'missing baryons' is solved in terms of the thermal and/or dynamical effects of the kinetic (at low redshifts z) and radiative (at high z) energy inputs from central active galactic nuclei, of which independent evidence is being observed. From these inputs we compute shape and z-evolution expected for $L_X - T$ correlation which agree with the existing data, and provide a predictive pattern for future observations.

Subject headings: galaxies: active nuclei – galaxies: clusters – radiosources – X rays: galaxies: clusters

1. INTRODUCTION

Groups and clusters of galaxies with their masses in the range $M \sim 10^{13} - 10^{15} M_\odot$ constitute the largest virialized structures in the Universe. They are dominated by the dark matter (DM) component, and are built up in a hierarchical sequence by gravitational infall and merging of smaller structures. Thus gravitational potential wells are set up with vast virial radii $R \sim 0.2 - 3$ Mpc, and large depths gauged by member velocity dispersions $\sigma^2 \sim GM/5R \sim (0.2 - 2 \times 10^3 \text{ km s}^{-1})^2$.

Such wells might be expected to also drag in and contain inside R all the baryons originally associated with the DM in making up the cosmic density ratio $\rho_b/\rho \approx 0.17$. Apart from a minor fraction locked up into galactic stars, these ought to be just reshuffled to constitute with the neutralizing electrons a diffuse intracluster plasma (ICP) in thermal and gravitational equilibrium at temperatures close to the virial values $kT \approx m_p \sigma^2/2 \sim 1 - 10$ keV.

On the other hand, the actual number density $n = \rho_b/m_p$ of the baryons (mostly protons with mass m_p) in the ICP is probed from its strong X-ray emissions $L_X \propto n^2 R^3 T^{1/2} \sim 10^{42} - 10^{46}$ erg s^{-1} produced by electron bremsstrahlung radiation. It is found that the baryonic fraction f_b is particularly low in poor clusters and groups despite these wells being, if anything, deeper (more 'concentrated', see Navarro et al. 1997) than gauged from σ^2 or $2kT$.

The finding stems from the correlation observed locally between L_X and T. Its generic form is outlined by the relation

$$L_X \propto f_b^2 \, \rho^{1/2} \, T^2 \, , \qquad (1)$$

provided by the brems emission law coupled with the virial scaling $kT \propto \rho R^2$ enforced by the DM gravity (Kaiser 1986). But the actual correlation differs sharply from the shape $L_X \propto T^2$ expected for wells filled up to a constant f_b; if anything, this ought to be bent upwards for groups with $kT < 2$ keV where line emission adds to the brems continuum. Instead, poor clusters and groups radiate much less than so expected, with the actual correlation bent *downward* to $L_X \propto T^3$ and steeper (see Osmond & Ponman 2004).

[1] Astrofisica, Dip. Fisica, Univ. 'Tor Vergata', Via Ricerca Scientifica 1, 00133 Roma, Italy.
[2] Astrophysics Sector, SISSA/ISAS, Via Beirut 2-4, 34014 Trieste, Italy.

These low radiation levels witnessing to scarcity of electrons-baryons have stirred a wide debate (see Evrard & Henry 1991; Ponman et al. 1999; Cavaliere et al. 2002; Lapi et al. 2005; Borgani et al. 2006; Bregman et al. 2007) over the mystery of the baryons missing from the ICP: are they lost somewhere within the wells, or outflown, or just limitedly infallen? Here we show that the second alternative is the fitting one, with some help from the third.

2. COOLING VS. HEATING

In sorting out these alternatives it helps to note that low emissivity $\mathcal{L}_X \propto n^2 T^{1/2}$ from the current ICP goes along with enhanced adiabat $K \propto kT \, n^{-2/3} \propto T^{5/3} \mathcal{L}_X^{-1/3}$ or excess specific entropy proportional to lnK, as in fact is measured (see Ponman et al. 2003; Piffaretti et al. 2005; Pratt et al. 2006).

Baryon sinks may occur within the wells due to radiative cooling, that affects mostly the densest and lowest entropy fractions of the ICP. Thereby these tend to lose their pressure support and further condense, radiate and cool even more, and so engage in the classic catastrophic course ending up into formation of plenty new stars (White & Rees 1978; Blanchard et al. 1992). What is left after a Hubble time is the ICP fraction originally in a hot dilute state, exhibiting a high residual entropy today (Voit 2005).

This indirect mechanism faces limitations, however. For example, cooling would steepen the local $L_X - T$ correlation to a shape $L_X \propto T^3$ only if it proceeded unscathed for a Hubble time throughout the hectic sequence of hierarchical mergers that build up a cluster of today (Voit 2005; for related evidence see Vikhlinin et al. 2007). Even so, the corresponding height still would fall short of the observed luminosity or entropy levels, unless so many stars condensed as to exceed the observational limits (Muanwong et al. 2002).

Finally, cooling does not even dominate the very 'cooling cores' at the center of the ICP; these are observed in many clusters to feature enhanced emissions and short cooling times, but their temperatures are bounded by $T_c \gtrsim T/3$ (Molendi & Pizzolato 2001; Peterson & Fabian 2006) at variance with the catastrophic trend intrinsic to cooling. So the latter must be offset by inputs of energy into the ICP, most likely from moderately active nuclei (AGNs) of central member galaxies (Binney & Tabor 1995; Voit & Donahue 2005).

But then such internal inputs can *directly* produce heating

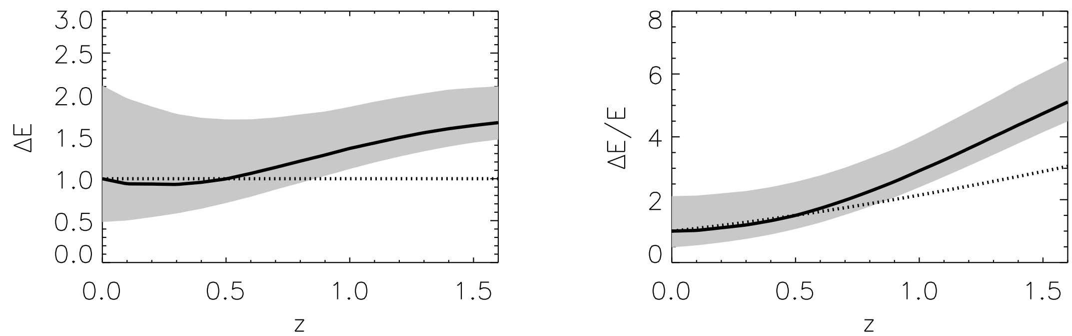

FIG. 1.— Left: the *solid* line shows the redshift evolution of the average energy input ΔE (normalized to the present) from AGNs (see Eq. [2]), with the *shaded* area illustrating the uncertainties (see text for details); the *dotted* line marks for reference the non-evolving case. Right: same for the ratio $\Delta E/E$ of the energy input to the ICP binding energy.

and outflows of the ICP so as to substantially lower L_X or equivalently raise the entropy. To affect the ICP at large, inputs of a few keVs per particle are required, and are easily provided by powerful AGNs energized by accreting supermassive black holes (BHs) in member galaxies (Wu et al. 2000; Cavaliere et al. 2002; Nath & Roychowdhury 2002; Lapi et al. 2005). These not only effectively control the central cool cores within 100 kpc, but also can raise K by some 10^2 keV cm^2 over much larger ICP masses (Lapi et al. 2005). In fact, imprints of such inputs in action are directly observed in the ICP out to $r \approx 3 \times 10^2$ kpc, where they excavate extensive cavities or launch far-reaching blastwaves (Bîrzan al. 2004; Nulsen et al. 2005; Forman et al. 2005; Cavaliere & Lapi 2006).

Taking up from Lapi et al. (2005), we show next how these AGN inputs provide a unified key to both the steep *shape* of the local $L_X - T$ relation and the apparently non-monotonic evolution of its *height*.

3. AGN INPUTS, KINETIC VS. RADIATIVE

What kind of AGNs are most effective in this context, depends on z and on the BH accretion rates $\dot{m}$ (Eddington units).

At $\dot{m} \lesssim 5\%$ and low $z \lesssim 0.5$ the dominant component to the outputs is constituted by 'kinetic power', in the form of high speed conical winds and narrow relativistic jets associated with radio emissions (see Churazov et al. 2005; Blundell & Kuncic 2007; Merloni & Heinz 2007; Heinz et al. 2007). Such outputs already in kinetic form end up with coupling a substantial energy fraction $f_k \approx 1$ to the surrounding medium, interstellar or ICP.

At higher $\dot{m}$ the radiative activity is held to be dominant (see Churazov et al. 2005), and is also well known to evolve strongly with z. So this is expected to take over in affecting the ICP despite the weaker photon-particle energetic coupling, bounded to levels $f_r \approx v/2c \approx 0.05$ by momentum conservation setting an outflow speed v. We stress that values of that order effectively account in terms of AGN feedback not only for the local shape of the $L_X - T$ correlation in clusters and groups that started up the present investigation, but also for several other observables: the galaxy stellar mass and luminosity functions (Springel et al. 2005); the luminosity functions of quasars and the mass distribution of relic BHs (Hopkins et al. 2006; Lapi et al. 2006); the correlation between these masses and the velocity dispersions in the host bulges (Vittorini et al. 2005).

On the other hand, velocities up to $v \sim 0.1 - 0.2\,c$ and metals spread out to some 10^2 kpc are widely observed around radioquiet quasars, indicating the action of efficient radiation-driven outflows or blastwaves (e.g., Pounds & Page 2006, Stockton et al. 2006). The radiation thrust may involve absorbtion in many atomic lines, or Thomson scattering of the continuum in the galactic plasma. Based on the latter, King (2003) has computed in detail outflows starting from the Compton-thick vicinities of the central BH and continuously accelerated to high speeds, that drive powerful blastwaves propagating into the outskirts of the host galaxy and beyond. At that point the Thomson optical depth retains values of several 10^{-2}, having decreased as $r^{-0.5}$ or slower in the hot galactic plasma with its flatter distribution relative to DM's.

TABLE 1
ESTIMATED CONTRIBUTIONS TO FEEDBACK

	$R_{k,r}$			
Comp.	r. quiet (0.9)	r. loud (0.1)	Total	$f_{k,r}$
rad.	1	1/2	0.95	$\lesssim 0.05$
kin.	0	1/2	0.05	1

The integrated input levels in these two regimes are related to a first approximation by the simple 'golden rule' $f\,\dot{m} \approx$ const, cf. Churazov et al. (2005). But their z-dependencies differ strongly as stressed by Merloni & Heinz (2007) and Heinz et al. (2007), with the kinetic power roughly constant (or slowly decreasing) out to $z \approx 0.5$, and the radiative power strongly increasing out to $z \approx 2.5$ if limited in its effects by weaker coupling.

These two components involve an activity fraction $R_{k,r}$ for radio loud or radio quiet AGNs, and contribute energies $W_{k,r}$ which combine after the reckoning given in Table 1 to yield the overall input

$$\Delta E(z) = R_k\, f_k\, W_k(z) + R_r\, f_r\, W_r(z)\ . \qquad (2)$$

As to $W_{k,r}$ we adopt the evaluations provided by Merloni & Heinz (2007); note that the kinetic contribution is mainly inferred from radio emission and from lack of X rays observed around radio loud AGNs, while the radiative contribution is measured mainly through the emissions from IR to X rays of radio quiet ones. The evolution of the overall $\Delta E(z)$ is reported in Fig. 1 (left) with uncertainties (shaded area) dominated by the jet beaming factors entering the determination of W_k.

Consider now that any action of the inputs ΔE on the ICP

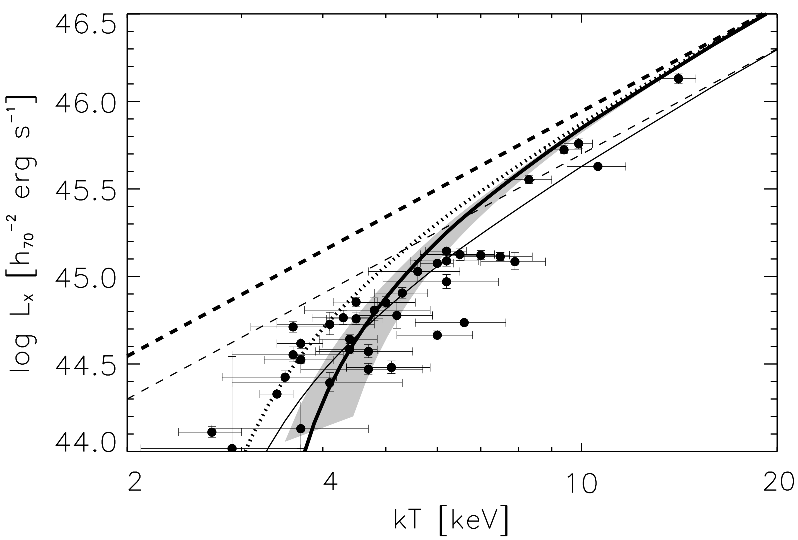

FIG. 2.— The $L_X - T$ relation at different redshifts z. The data (*filled circles*) are from the high-z (average $z \approx 0.7$) sample by Branchesi et al. (2007). The *thick* lines refer to $z = 0.7$: the *dashed* one is the relation in the absence of energy inputs; the *solid* one shows the model result we find from Eq. (4) on using the z-dependence of $\Delta E/E$ after Eqs. (2) and (3); the *dotted* one is for a non-evolving ΔE. For comparison, the *thin* lines refer to $z = 0$: the *dashed* one is the relation in the absence of energy inputs, and the *solid* one shows the model result for $z = 0$, that provides a good fit to the local data (Lapi et al. 2005, see their Figure 3).

is to be gauged against its unperturbed total energy E (thermal plus gravitational), with modulus scaling as $E \propto kT\, M_b \propto f_b\, \rho^{-1/2}\, T^{5/2}$; the dependencies on z and T are given in full by

$$E(z,T) \approx 1.5 \times 10^{63}\, \frac{f_b}{0.12}\, \frac{H(0)\, \Delta_{\rm v}^{1/2}(0)}{H(z)\, \Delta_{\rm v}^{1/2}(z)} \left(\frac{kT}{6\ \mathrm{keV}}\right)^{5/2}\ \mathrm{erg}\ . \tag{3}$$

Here the DM density $\rho \propto H^2\, \Delta_v$ internal to a virializing cluster or group has been taken from the standard 'top hat' collapse model for structure formation, in terms of the running Hubble parameter $H(z)$ and the contrast $\Delta_{\rm v}(z)$ at virialization (see Peebles 1993); in the Concordance Cosmology the resulting behavior for $z \lesssim 1$ is close to $\rho(z) \propto (1+z)$.

The above expression for E strictly holds for an isothermal ICP filling an isothermal DM potential well; however, for a well shape after Navarro et al. (1997) and/or a polytropic distribution of the ICP with the appropriate index $\Gamma \approx 1.1-1.2$ the result is not significantly altered; in particular, it is unaltered the slow decrease for $z \gtrsim 0.5$ due to smaller masses associated with earlier potential wells. Normalization is made to the value $f_b = 0.12$ provided by X-ray and Sunyaev-Zel'dovich observations of ICP in rich clusters (see LaRoque et al. 2006; Ettori et al. 2006); the discrepancy from the value 0.14 (expected on subtracting the stellar component from the cosmic value 0.17) is likely due to the parallel, second order effect of the AGN feedback causing external preheating and entropy rise of the gas, which limit its infall into the gravitational wells as discussed by Lapi et al. (2005). These authors stress that preheating by itself would also cause wider distributions of the ICP in poor clusters and groups; but in these smaller potential wells the effect is actually offset by their higher concentration, resulting in nearly invariant profiles as observed, e.g., by Pratt & Arnaud (2003) and by Pratt et al. (2006).

Thus the effective input at each z is given by the ratio $\Delta E/E$, that we represent in Fig. 1 (right) after normalizing it to the value needed to fit the local $L_X - T$ relation; this corresponds to coupling levels $f_r \approx 0.05$, discussed above in this Section.

4. RESULTS

Given this input, we compute the resulting L_X on extending to higher z the approach that yields a fitting shape for the local $L_X - T$ all the way from 10 to $1/2$ keV (see Lapi et al. 2005, their Fig. 3). So we substantiate Eq. (1) with the baryonic fraction $f_b\,[1-\Delta E/2E]$ affected by internal AGNs, to read

$$L_X(z,T) \propto f_b\, H(z)\, \Delta_{\rm v}^{1/2}(z)\, \left[1 - \frac{\Delta E(z)}{2\,E(z,T)}\right]^2\, T^2\ . \tag{4}$$

The factor in square brackets is the simple, converging result obtained from detailed numerical modeling; specifically, we use two oppositely extreme models of thermal outflows and of dynamical ejection of the ICP out of the DM potential wells, caused by finite perturbances (blastwaves) driven by AGNs, see Lapi et al. (2005). The factor $1/2$ reflects the close equipartition of kinetic and thermal energy in blasts with Mach numbers $\mathcal{M} \approx 1.5-2$ such as involved in this context. The prefactor $H(z)\, \Delta_{\rm v}^{1/2}(z)$ again expresses $\rho^{1/2}(z)$.

Fig. 2 shows two snapshots of the $L_X - T$ relation predicted after such modeling. The one at $z = 0$ (thin solid line) steepens toward low temperatures due to the T dependence of E given by Eq. (3); it provides a good fit to the local data, as discussed by Lapi et al. (2005). For $z \gtrsim 0.5$ we expect the $L_X - T$ relation (see the thick solid line) to *steepen* yet relative to that at $z = 0$, due to the increase of $\Delta E/E$ with z; such an evolved relation agrees with the current observational evaluations, including the precise ones at high T provided by Branchesi et al. (2007). Note that a constant ΔE would yield the dotted line that systematically overarches most data points.

Fig. 3 shows our prediction for the evolution in rich clusters of the X-ray luminosity at a given T, expressed as $\mathcal{A}(z) \equiv L_X(z)/L_X(0)$; the data by Branchesi et al. (2007) have been reported with the same temperatures and local $L_X - T$ relation they adopt.

Our result agrees with the existing data, with their non-monotonic *trend* currently just looming out and their large

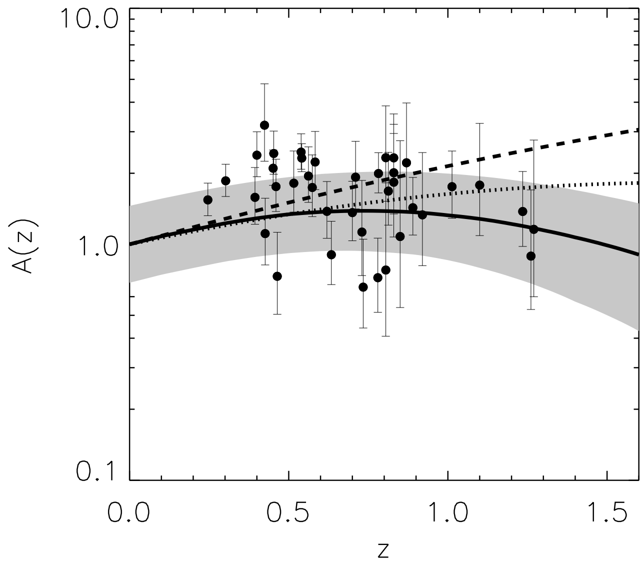

FIG. 3.— Redshift evolution of $\mathcal{A}(z) = L_X(z)/L_X(0)$, see Section 4. The *solid* line is the evolution from using Eq. (4) with $\Delta E/E$ as in Fig. 1, right panel; the *dotted* line is for a constant input ΔE; the *dashed* line represents the scaling expected in the absence of energy inputs. Data (*filled circles*) are from Branchesi et al. (2007).

scatter. In our modeling scatter is mainly contributed by variance in the evaluations of the jet beaming factors (see Merloni & Heinz 2007), conceivably reflecting physical variations. As to trend, our run of $\mathcal{A}(z)$ predicts a clear non-monotonic pattern, with a rise out to $z \approx 0.5$ and then a decrease to higher z. The key feature to the slow *rise* is that the kinetic power $W_k(z)$, with its lack of strong evolution, can barely chase the cosmological increase of all internal densities out to $z \approx 0.5$. But at higher z the evolution is curbed or *reversed* by the radiative input emerging; this occurs by virtue of its strongly positive evolution common to all radiative AGN activities from IR to X rays, despite the weaker coupling but with some help from the decrease of $E(z)$.

5. DISCUSSION AND CONCLUSIONS

The results of our computations yield a slow, non-monotonic pattern of $L_X(z)$ at given T. This stems from basic features of the internal AGN outputs, that comprise two different components: kinetic and radiative, combining as follows.

i) Kinetic power at low $\dot{m}$ and z. An extreme interpretation attributes this to the Blandford & Znajek (1977) mechanism for extraction of BH rotational energy from the large reservoir accrued by past accretion events. Low rates $\dot{m}$ (likely from trickling accretion related to cooling in the host galaxy) just provide enough material to hold in the accretion disk the magnetic field that threads the BH horizon and induces significant outward Poynting flux.

ii) Radiative power, prevailing at higher z and $\dot{m}$. This is widely held (Springel et al. 2005; Cavaliere & Menci 2007; also Conselice 2007) to be driven by violent galaxy interactions and mergers; their rates increase sharply for $z \gtrsim 0.8$ in the Concordance Cosmology, so as to drive large accretion rates onto the central BHs.

Besides interpretations, the fact stands that the two processes with their different couplings nearly match at $z \approx 0.5$, in agreement with the golden rule. At lower z the kinetic mode is granted a leading edge by its stronger coupling with the ICP; for $z \gtrsim 0.5$, instead, the radiative mode with its weaker coupling takes over by virtue of its strong evolution.

To conclude, we submit the missing baryons from the ICP of poor clusters and groups to be explained in terms of the energy feedback from internal AGNs, a straight extension of the inputs that limit the cooling cores. In closer look, we predict for $L_X - T$ a non-monotonic pattern primarily reflecting the two different types of evolution in the AGN activities: closely constant as for the kinetic component, and strongly positive for the radiative one. At given T, the former just slows down the rise of $L_X(z)$ driven by the cosmogonic density increase, whilst the latter with $f_r \approx 0.05$ can reverse the trend sharply. While for the body of the current data with their scatter the gross average may still be formally compatible with a monotonic rise (Pacaud et al. 2007), a non-monotonic pattern is already looming out from luminous high-z clusters, consistent with our prediction.

In a wider perspective, we argue that the X-ray emission $L_X(z)$ can independently probe the evolution of the kinetic power activity mainly related to radio loud AGNs. We submit that the independent data concerning L_X already indicate for this component a nearly constant, if not a weakly *negative* evolution for low $z \lesssim 0.5$; this constitutes an emerging feature of the kinetic power, with a precedent only in the lack of evolution (see Caccianiga et al. 2002) of the BL Lac Objects, themselves kinetically loud sources. The link we establish between $L_X(z)$ and $W_k(z)$ will provide complementary information to direct statistics of weak radio sources (see discussion by De Zotti et al. 2005), which is hindered by incompleteness and by confusion from diffuse galactic contributions.

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